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## RADIATION HARDNESS OF $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}/\text{GaAs}$ TANDEM SOLAR CELLS

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The radiation hardness of a two-junction monolithic  $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}/\text{GaAs}$  cell with tunnel junction interconnect is investigated. Related single-junction cells are also studied to identify the origins of the radiation losses. The optimal design of a  $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}/\text{GaAs}$  cell is discussed. The air mass (AM)0 efficiency of an optimized tandem cell after irradiation with  $10^{15} \text{ cm}^{-2}$  1 MeV electrons is estimated to be 20% using currently available technology.

### INTRODUCTION

Two-junction monolithic device efficiencies have recently surpassed those of single-junction devices (Chung, 1989; Olson, 1990). These devices present the advantages of higher efficiencies with lower currents and low temperature coefficients while avoiding use of a mechanical stack. A monolithic, two-junction device with a tunnel-junction interconnect can easily be incorporated into existing systems without changes in the wiring or processing schemes. The advantages of the choice of  $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$  and GaAs for fabrication of a monolithic, two-junction device including a current state-of-the-art efficiency of 27.3% (Olson, 1990) are presented in detail elsewhere (Olson, 1991).

Although the  $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}/\text{GaAs}$  tandem cell is very attractive for space applications because of its high efficiency, ease of introduction into existing GaAs processing lines, low temperature coefficient, and relatively low current and high voltage, its sensitivity to radiation has not been established. The sensitivity of the GaAs bottom cell to radiation can easily be extrapolated from the literature (for example, Yamaguchi, 1985; Fan, 1980; Markvart, 1990). There is also substantial data on the radiation sensitivity of InP (for example, Yamaguchi, 1988), but it is not known whether  $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$  responds to radiation in a similar manner, and it has not been established how the added complexity of a multijunction device may affect the radiation sensitivity. This paper presents data on the effect of electron radiation on the performance of the  $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}/\text{GaAs}$  cells and discusses the implications of these data in terms of the design of the tandem cell and the anticipated radiation hardness. It will be shown that using a thin  $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$  top cell not only improves the current matching but reduces the radiation damage in the top cell.

## EXPERIMENTAL METHOD

Schematics of the device structures used in this study are shown in Fig. 1. The structures were grown in a vertical, air-cooled reactor at one atmosphere using organometallic chemical vapor deposition, the details of which are described elsewhere (Olson, 1986). The group III source gases were trimethylindium, trimethylgallium and trimethylaluminum; the group V source gases were arsine and phosphine. The dopant sources were diethylzinc, carbon tetrachloride, disilane, and hydrogen selenide. All of the structures were grown at 700°C, with the exception of the back-surface field of the top cell and the preceding GaAs layer, which were grown at 625°C. The phosphides were grown under a V/III (ratio of group V sources to group III sources) of 30 for the  $10^{17} \text{ cm}^{-3}$  p-type layers and 240 for the  $10^{18} \text{ cm}^{-3}$  n-type layers. The base GaAs layer was grown with a V/III of 35. Most of the layers were grown with a growth rate of 100 nm/min. The tunnel junction layers were grown at lower rates, as low as 10 nm/min. The front and back contacts were made by electroplating gold. A heavily doped GaAs layer was used for the top contact. This layer was removed before adding the double layer antireflection (AR) coating ( $\text{ZnS}$  and  $\text{MgF}_2$ ). A more detailed description of the cell fabrication is given elsewhere (Olson, 1990).

The cells were irradiated to a fluence of  $10^{15} \text{ cm}^{-2}$  of 1 MeV electrons by B. Anspaugh at the Jet Propulsion laboratory. The devices were characterized at both the Solar Energy Research Institute (SERI) and Spectrolab before and after irradiation. The device parameters reported here were measured by K. Emery at SERI for one-sun, AM1.5 global conditions. The tandem cells were measured after adjusting the spectrum of the solar simulator to achieve the appropriate currents for two reference cells (with spectral response curves similar to those of the top and bottom cells), as described by Glatfelter, 1987. The spectral response curves were measured using a monochromator-based system. The relative response of this system was calibrated using a thermopile. The absolute calibration was obtained by integrating the product of the spectral response curve and the solar spectrum and comparing this with the short-circuit current ( $J_{\text{SC}}$ ). The separate top- and bottom-cell quantum efficiency curves for the tandem cell were measured using light biasing and, in some cases, electrical biasing.

AlInP	25 nm	Se
GaInP	100 nm	Se
GaInP	1000 nm	Zn
GaAs	12 nm	Zn
GaAs	12 nm	Se
AlGaAs	100 nm	Se
GaAs	100 nm	Se
GaAs	3500 nm	Zn
GaAs substrate		Zn

(a)

AlInP	25 nm	Se
GaInP	100 nm	Se
GaInP	600 nm	Zn
GaInP	40 nm	Zn
GaAs substrate		Zn

(b)

GaInP	800 nm	Zn
GaAs	25 nm	C
GaAs	20 nm	Si
GaInP	25 nm	Se
GaAs	100 nm	Se
GaAs	3000 nm	Zn
GaInP	50 nm	Zn
GaAs substrate		Zn

(c)

Figure 1. Device structures for the (a) tandem cell, (b) thin top ( $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$ ) cell, and (c) bottom (GaAs) cell. The thicknesses and dopant for each layer are indicated. The alloys are all nominally lattice matched to GaAs. The thick ( $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$ ) top cell had a structure as shown in (b) except that the base layer was 6  $\mu\text{m}$  instead of 0.6  $\mu\text{m}$ .

## RESULTS

Four device structures were chosen for the study (as shown in Fig. 1): a tandem cell, top and bottom cells similar to those in the tandem cell, but grown separately, and, a thick top cell. The bottom cell included a GaAs tunnel junction and a  $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$  layer of thickness comparable to a top cell so that the single-junction bottom cell is optically very similar to the bottom cell in the tandem structure. The tandem cell differed from the single-junction cells as to the passivating layers on the front and back and the dopants used in the tunnel junction. The results of the study imply that these differences are not major factors in determining the radiation sensitivity of the device. Although it is possible to separately evaluate the currents of the two junctions in the tandem cell, it is not possible to separately evaluate the voltages. Thus, the single-junction cells were grown for this purpose. In Fig. 1, the GaAs contacting layer, Au grid, and AR coating are not shown. The heavily doped GaAs layers used for the tunnel junction and contacting layer approached  $10^{19} \text{ cm}^{-3}$  in carrier concentration. The emitter layers were doped n-type with Se to about  $10^{18} \text{ cm}^{-3}$ . The  $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$  base layers had a hole concentration of about  $10^{17} \text{ cm}^{-3}$ , while that of the GaAs base layers was  $2.5 \times 10^{17} \text{ cm}^{-3}$ . The thick top cell had the same structure as shown for the thin cell (Fig. 1b), but it had a base thickness of  $6 \mu\text{m}$ . The thick  $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$  top cell would not be used in an actual tandem cell structure, but it gives us more information about the radiation hardness of  $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$  itself. Four devices were fabricated for each device structure. We present here the average results, or specific results for a representative cell. After analysis of the four device structures, it became apparent that the doping level of the GaAs base layer is a very important parameter. An additional conventional GaAs device was grown with a base doping level of  $2 \times 10^{16} \text{ cm}^{-3}$ . This device had  $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$  as the passivating layers for both the front and back surfaces.

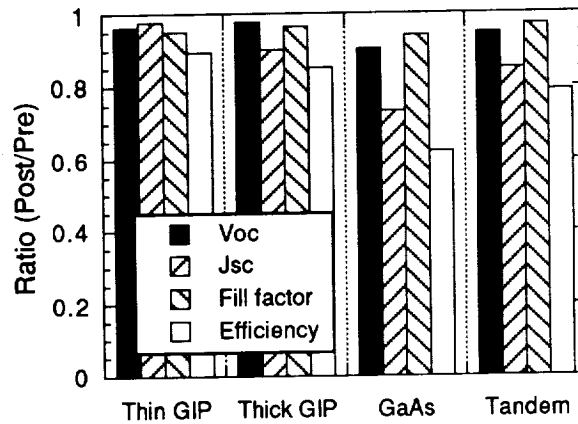


Figure 2. The degradation of device parameters after irradiation with  $10^{15} \text{ cm}^{-2}$  1 MeV electrons.

Figure 2 shows the relative performance of the four devices after irradiation. The relative values shown here were measured under AM1.5 conditions, but we expect that the relative performance under AM0 would be similar. The degradation of current in the thin top cell was negligible compared to the uncertainty of the measurement. However, the open-circuit voltage ( $V_{OC}$ ) and fill factor (FF) both degraded by about 5%. The thick top cell did show a significant (10%) loss of current, indicating that the  $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$  base diffusion length does decrease after irradiation, highlighting the advantage of using a top-cell thickness less than the post-radiation diffusion length. The degradation of the GaAs bottom cell was dominated by the loss of current (more than 25% of the current was lost) with significant (5% - 10%) degradation also observed in the  $V_{OC}$  and FF. Clearly, both of the  $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$  cells showed superior radiation hardness to the GaAs cell. The degradation of the tandem cell was less than that of the GaAs cell but greater than that of the  $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$  cell, as would be expected for the  $V_{OC}$  and

FF. The better performance of the  $J_{SC}$  (which would be expected to reflect the GaAs bottom cell since it degraded more) is likely to be due to a lack of current matching in the device before irradiation, (*i.e.*, before irradiation the bottom cell produced more current than the top cell, indicating that the top cell was thicker than optimal).

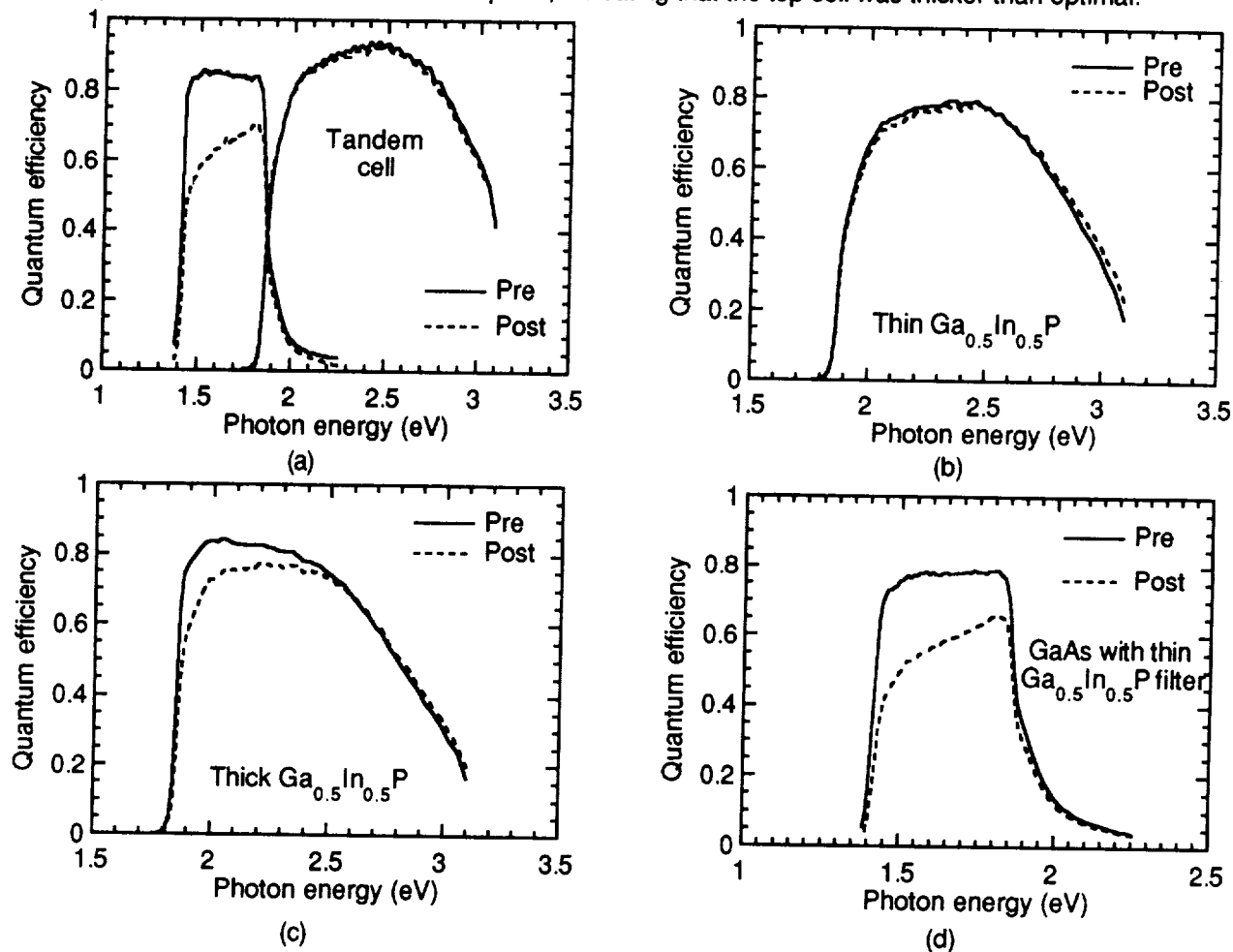


Figure 3. Quantum efficiency curves for (a) a tandem cell, (b) a thin top cell, (c) a thick top cell, and (d) a bottom cell before and after irradiation with  $10^{15} \text{ cm}^{-2}$  1 MeV electrons. These data and the data in Fig. 2 pertain to the same samples.

Figure 3 shows the quantum efficiency curves for the four cells both before and after irradiation. What appears to be poor red response in the top cell (Figs. 3a and 3b) is a result of the thinness of the top cell. Some of the light passes through and is collected by the bottom cell, resulting in a tail toward the high-energy side of the quantum efficiency curves as shown in Figs. 3a and 3d. The thick  $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$  cell shows about a 10% loss in  $J_{SC}$  after irradiation. As can be seen from Fig. 3c, most of this loss is in the red response of the cell. This loss is substantially greater than the loss observed for the thin  $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$  cell. For the thin cell, the loss in quantum efficiency was not consistent between the four devices measured. Two devices lost more toward the blue end of the spectrum, and two lost more toward the red end of the spectrum. However, none of the four devices lost more than 3% of the total current, implying that these differences are less than the uncertainty of the experiment. The GaAs cell degraded significantly in red response. From the literature, this large degradation can be directly related to a high doping concentration in the base of the cell, and it motivated the study presented below for a GaAs cell with a lower base doping level. One of the GaAs bottom cells had a low FF (caused by a shunt) before irradiation. This device degraded more than the others (to 56% compared to 62% of beginning of life efficiency), so the data

for that device were not averaged with those of the other devices. The results from the tandem cell (Fig. 3a) are consistent with those from the single-junction cells (Figs. 3b and d). That is, the top cell showed almost no degradation while the bottom cell showed substantial degradation.

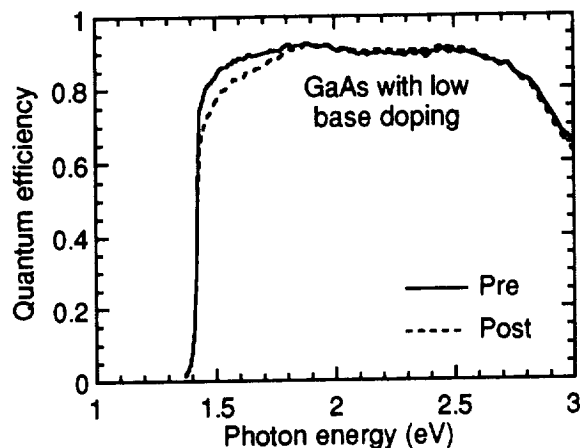


Figure 4. Quantum efficiency before and after electron irradiation for a GaAs cell with a base doping of  $2 \times 10^{16} \text{ cm}^{-3}$ .

Figure 4 shows quantum efficiency results from a conventional single-junction GaAs cell grown with a lightly doped base layer ( $2 \times 10^{16} \text{ cm}^{-3}$ ). This sample was irradiated on a different date than the other samples. However, other cells irradiated on the same date but that had larger base doping levels showed degradation similar to that shown in Figs. 3a and 3d. It should be noted that the degradation in FF for the lightly doped GaAs cell was comparable to those for more heavily doped cells and similar to that of the GaAs bottom cell presented above (Figs. 2 and 3d). However, the  $V_{OC}$  showed a somewhat larger degradation (to 85% of beginning-of-life (BOL) compared with 90% of BOL for the more heavily doped cells).

## DISCUSSION

The thin  $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$  top cell clearly showed excellent radiation resistance, retaining 90% of its BOL efficiency. However, the GaAs bottom cell showed large degradation, primarily because of degradation of the  $J_{SC}$ . This large degradation in the current of the GaAs n-on-p bottom cell can be related to a high doping level in the p-type base region (Yamaguchi, 1985; Fan, 1980). The results presented here are consistent with the predictions of Yamaguchi and Fan. Specifically, the GaAs cells fabricated with a base doping level of  $2 \times 10^{16} \text{ cm}^{-3}$  showed substantially less degradation than those with high base doping levels. Yamaguchi estimated that the optimal base doping level is  $2 \times 10^{16} \text{ cm}^{-3}$ , while Flood (1987), in reporting Fan's work, shows a very broad end-of-life (EOL) efficiency maximum centered on  $1 \times 10^{16} \text{ cm}^{-3}$ . This difference can be predicted from analyses similar to that presented by Yamaguchi, 1985. The change in minority carrier diffusion length  $L$  with irradiation is related to  $K\phi$  by

$$\Delta(1/L^2) = K\phi$$

where  $K$  is the damage constant and  $\phi$  is the electron flux. The better performance is a result of both a smaller  $K$  for the more lightly doped p-type GaAs, and a longer diffusion length for the preirradiated material. It is not clear which of these effects is more important since Yamaguchi (1985) shows very little variation of  $K$  with p-type doping level in this range, while Fan shows  $K$  almost directly proportional to the p-type doping level (this work was

originally reported by Fan (1980) and subsequently included in reviews by Markvart (1990) and Flood (1987)).

In the tandem cell chosen for this study, the largest degradation came from a loss of current in the bottom cell. This is especially problematic for a series-connected device because a similar amount of current is lost from the top cell simply because it can't be carried out of the device. This limitation of series-connected devices has discouraged many from considering series-connected tandem cells for use in space. However, this is not a necessary loss. If the tandem cell is grown with a lower base doping level in the bottom cell, the loss of current for the bottom cell will be substantially less. Using the degradation of the spectral response of the lightly doped GaAs and applying this loss to the pre-radiation spectral response curve of the bottom cell shown in Fig. 3d, the expected EOL current for a bottom cell with a lightly doped base layer would be 91% of the BOL current instead of the 73% measured here. Even this lower value of 91% is still a substantially greater loss than the loss in current measured for the top cell, implying that there will still be some loss after irradiation associated with the series connection. However, this loss does not prevent the device from being useful. In fact, as shown below, this loss from series connection can be helpful in tailoring the performance profile of the solar cell.

In some cases, it is advantageous to have extra power at the beginning of a mission, and other times it would be more useful to have a constant power source throughout the mission. Table I shows the efficiencies we estimate would be obtained for a tandem cell of the quality of the 27.3% efficient AM1.5 global cell if it were redesigned for AM0 one-sun efficiency. The redesigning of the device involves only two changes: (1) a decrease of the base doping level of the bottom cell to improve its radiation resistance and, (2) an adjustment of the top cell thickness to achieve current matching under the desired conditions. Specifically, it was assumed that the current of the bottom cell would degrade to 91.3% of BOL, but that the voltage would degrade to 85% of BOL, and that the total BOL AM0 current of the device (*i.e.*, the sum of the top and bottom cell currents) would be 33.4 mA/cm<sup>2</sup>. The 24.4% efficiency was calculated from device parameters of 2.296 V, 16.7 mA/cm<sup>2</sup>, and 87% FF. The efficiencies were estimated for optimizing both BOL and EOL performance. This was done by adjusting the top cell thickness so that the device would be current matched at BOL or EOL, respectively. It is clear that the choice of optimization for BOL or EOL makes little difference in the absolute efficiency. However, the ratio of EOL to BOL changes from 82% to 87%, which may be significant depending on the desired performance profile. Most important to note is that in either case we estimate that with appropriate optimization and existing Ga<sub>0.5</sub>In<sub>0.5</sub>P/GaAs technology an EOL, AM0 efficiency of 20% can be achieved.

We emphasize that this study only used a small number of cells and that, although we investigated ways to improve the stability of the current, we have not investigated ways to improve the stability of the voltage, leaving some room for improvement. Additional studies are planned for tandem devices with lower base doping and appropriate top cell thicknesses.

Table I. Estimated AM0 efficiencies for tandem cells before and after irradiation with 10<sup>15</sup> cm<sup>-2</sup> 1 MeV electrons.

Tandem Cell	Before (%)	After (%)	Ratio E.O.L/BOL (%)
Optimized for BOL	24.4	20.0	82
Optimized for EOL	23.7	20.7	87

## SUMMARY

The radiation hardness was investigated for a monolithic, two-junction tandem  $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}/\text{GaAs}$  cell with a tunnel-junction interconnect. The device was shown to retain approximately 80% of its beginning of life efficiency. The primary degradation was a result of a large loss of current from the bottom cell. This degradation can be controlled by lowering the base doping level, although this may contribute to an increased degradation of the voltage. The top cell degradation was minimal with end-of-life parameters  $J_{\text{SC}}$ , 98%;  $V_{\text{OC}}$ , 96%; FF, 95%; and efficiency, 90% of BOL. This degradation is minimized as a result of the thin base layer in the top cell. It would appear that the damage coefficients for  $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$  lie between those of GaAs and InP, but this depends on the doping levels of interest. With low base doping and appropriate top-cell thickness, an end-of-life ( $10^{15} \text{ cm}^{-2}$  1 MeV electrons) AM0 efficiency of 20% can be achieved with existing technology.

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